Kern Canyon Fault Quartz Piezometry and Thermometry: How Weak are Rocks in a Deep Fault?

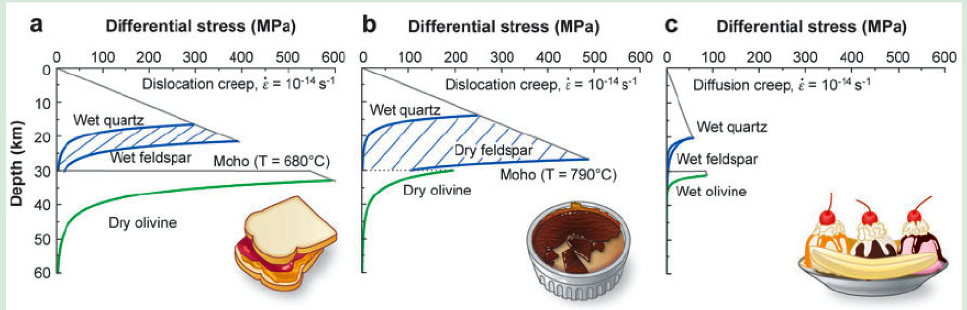
Rebekah Tsigonis and Elisabeth Nadin Department of Geology and Geophysics

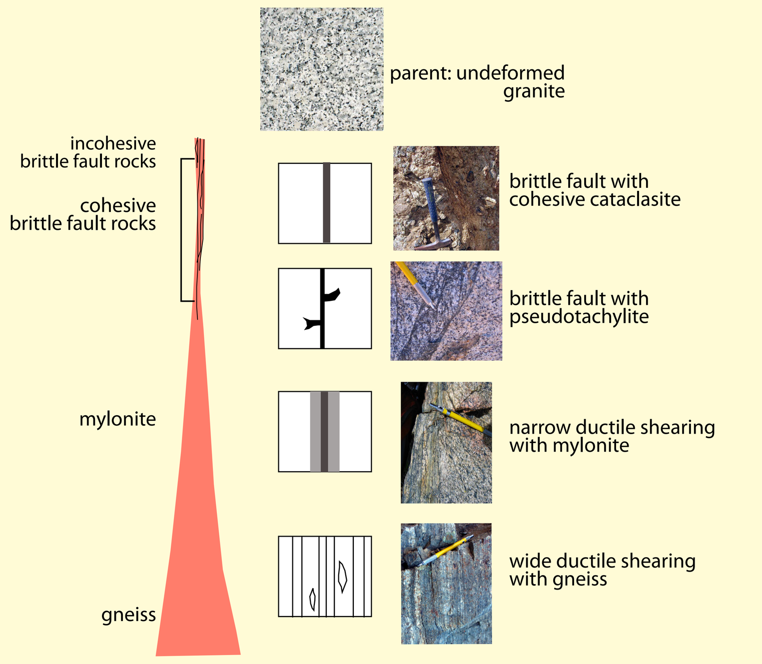
Abstract

This project is an investigation of the strength of rocks from 10-25 kilometers depth in the Kern Canyon Fault in the Sierra Nevada. When this fault was active, it behaved similarly to the San Andreas Fault in California and the Denali Fault here in Alaska. Deep sections of this ancient fault were brought to the surface of the Earth through erosion. Using a method known as piezometry, I was able to measure the sizes of deformed quartz grains in rock samples, which inversely relates to the amount of stress that the rocks experienced during faulting. I also used a technique known as titanium-in-quartz thermometry (TitaniQ) to determine the temperature of the rocks during faulting deformation episodes. Via the Electron Microprobe in the Analytical Facility at UAF, I was able to measure the amount of titanium present in the deformed quartz grains which directly correlates to the temperature at which these crystals formed. In combining the calculations for stress and temperature of deformation, the strain rate exhibited on these rocks was determined which is used to better understand how weak or strong rocks are at different depths within fault zones.

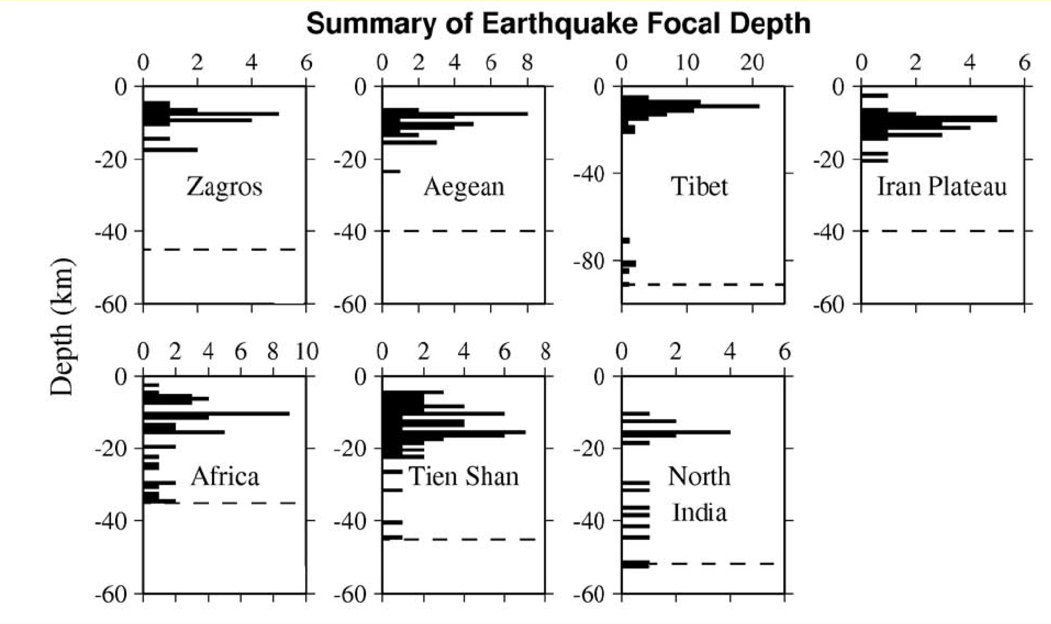
Background

A current query in the geosciences and what this project is interested in determining is how the strength of rock varies with depth. There are three different hypotheses. The first is known as the jelly sandwich. This proposal is that the crust is strong both near the surface of the earth and at depth (the bread), but that there is a zone in between where the crust is very weak (the layer of jelly). A second theory is the crème brûlée model where the crust is strong just near the surface and is then weak at depth. The third theory is the banana split model in which the crust is strong all the way through (bananas), except where faults intersect it (ice cream in the middle).





This diagram shows the increase in width of faults with depth and the change in the behavior of rock deformation with depth. The pink wedge represents a cross section of a fault.



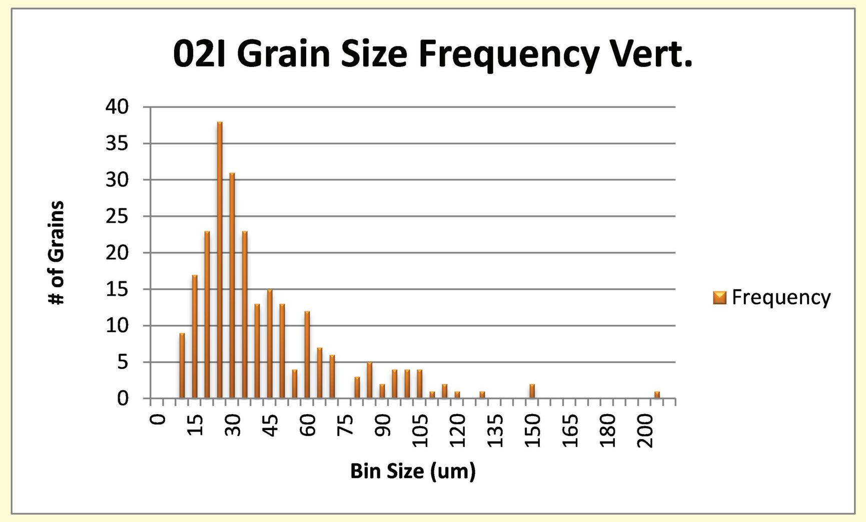
Known frequency of earthquakes at depth. Earthquakes most commonly occur between 5 and 15 kilometers depth. Why this happens is still under debate, but the flow of rock at these depths could play a key role.

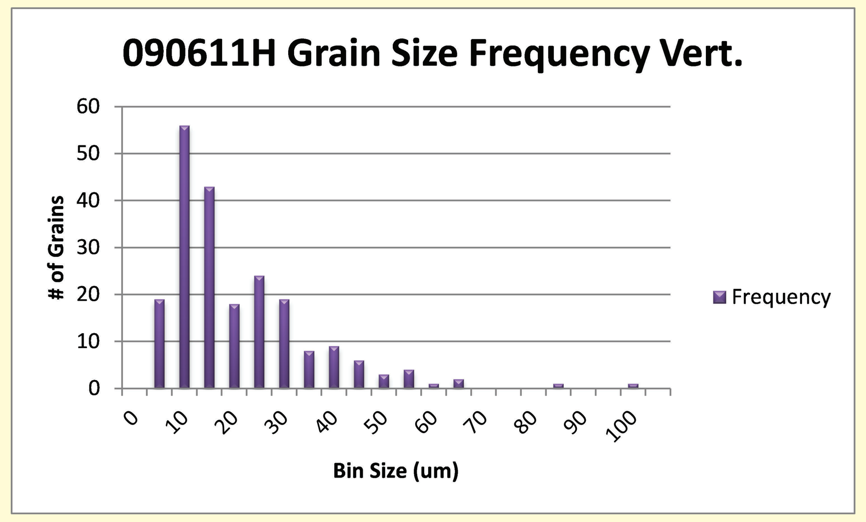
Sheared rocks in the foreground and the gully in the background define the surface trace of the Proto-Kern Canyon Fault in the Sierra Nevada

Piezometry

In 2003, Stipp and Tullis presented a new piezometer (pressure measurement) for quartz-rich rocks that relates the size of the quartz grains in the rock to the stress that the rock experienced. This piezometer showed that grain size is inversely proportional to stress experienced by the rock. One of my objectives in this project was to use this piezometer to calculate stress for different depths along the fault. In order to measure the sizes of the quartz crystals in my samples, I studied thin sections-polished rock ~30 um thick, glued with epoxy onto a glass slide. I photographed the thin sections through a petrographic microscope and used the computer program ImageJ to measure the length of the deformed quartz grains in both the horizontal and vertical directions.

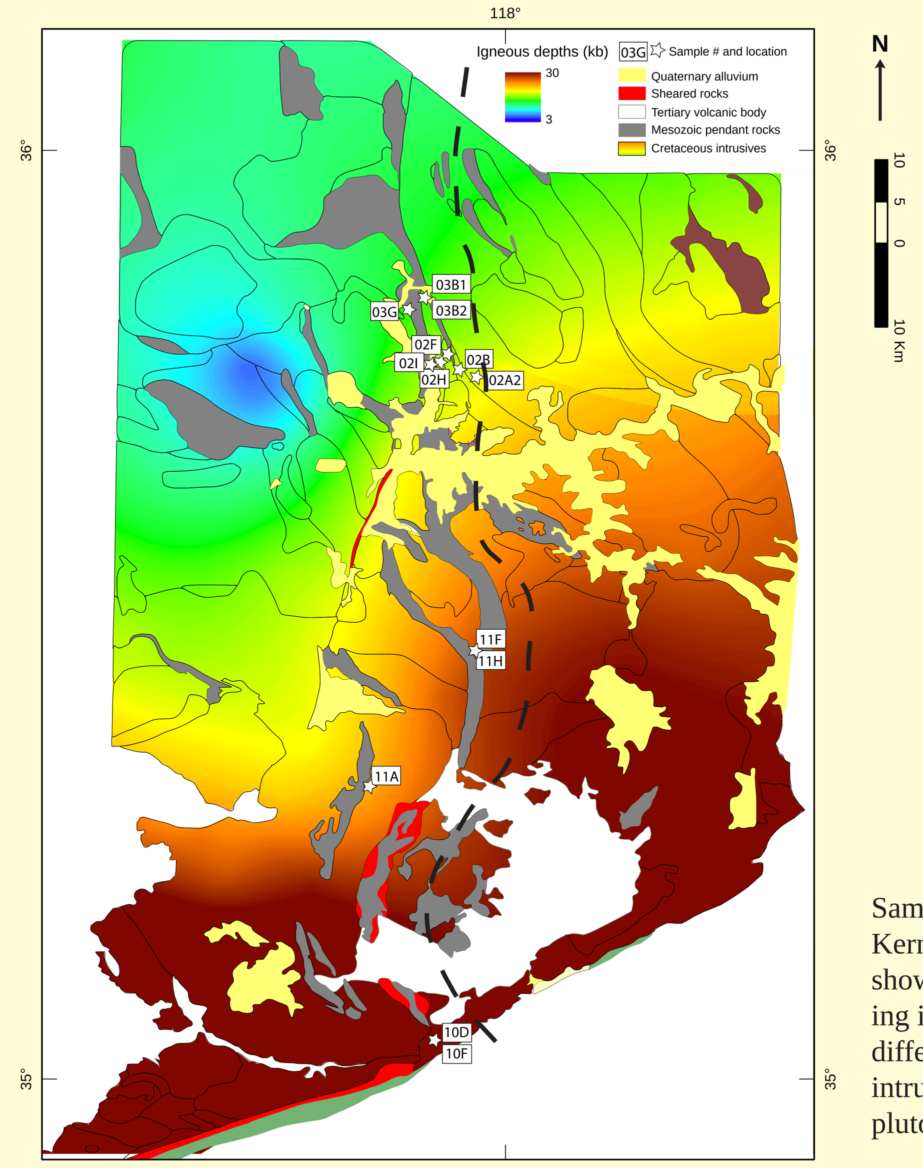
Once I measured the grains, I plotted histograms to show the most statistically probable grain size for each sample. Using these grain sizes, I calculated the stress each individual sample experienced, and thus the rock strength, via the equation proposed by Stipp and Tullis: D = 10^(3.56)*σ^(-1.26). D represents the grain size in micrometers and σ represents the rock strength.



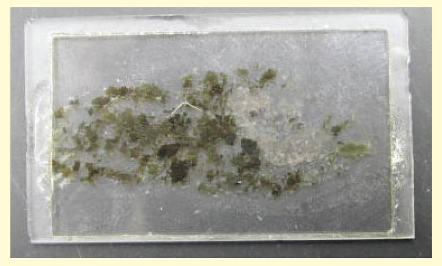


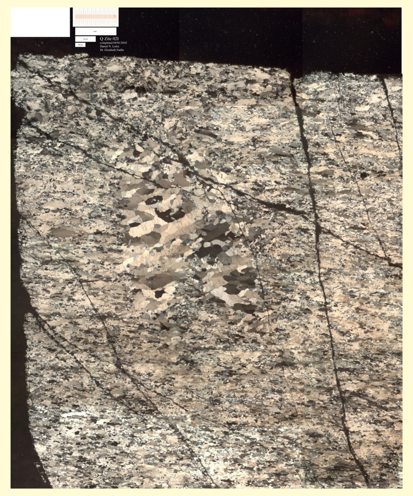
TitaniQ

TitaniQ is a geothermometer that uses the concentration of titanium present in quartz grains to determine the temperature at which crystallization took place. The higher the concentration of titanium present within the crystal structure, the higher the temperature of deformation. After coating the samples with carbon to reduce the scatter of the electron beam, I used the electron microprobe in the analytical facility at UAF to measure the concentrations of titanium in specific quartz grains. Some samples were found to have no titanium present within the grains but this was due to a low concentration of titanium in the host rock versus a very low recrystallization temperature. Therefore, I had to extrapolate on the deformation temperature on certain samples from the temperature of nearby samples found to have an adequate concentration of titanium. I then calculated the strain rate using an equation proposed by Hirth et.al. (2001).



Sample locations from along the Kern Canyon Fault, which is shown as a dashed line. The coloring in the background represents different depths at which plutonic intrusions crystallized. Individual plutons are outlined in black.





Above: Photograph of a thin section.
Right: Photograph of sample 02I through a petrographic microscope.

Sample		Statistical mean Grain Size (um)	Rock Strength (Mpa)
081102B	Horz.	20	62.06
	Vert.	20	62.06
081102H	Horz.	20	62.06
	Vert.	20	62.06
081103B1	Horz.	22.5	56.52
	Vert.	15	77.98
081103B2Z	Horz.	10	107.58
	Vert.	20	62.06
081103G	Horz.	15	77.98
	Vert.	15	77.98
090611H	Horz.	10	107.58
	Vert.	10	107.58
02I	Horz.	35	39.81
	Vert.	25	51.99

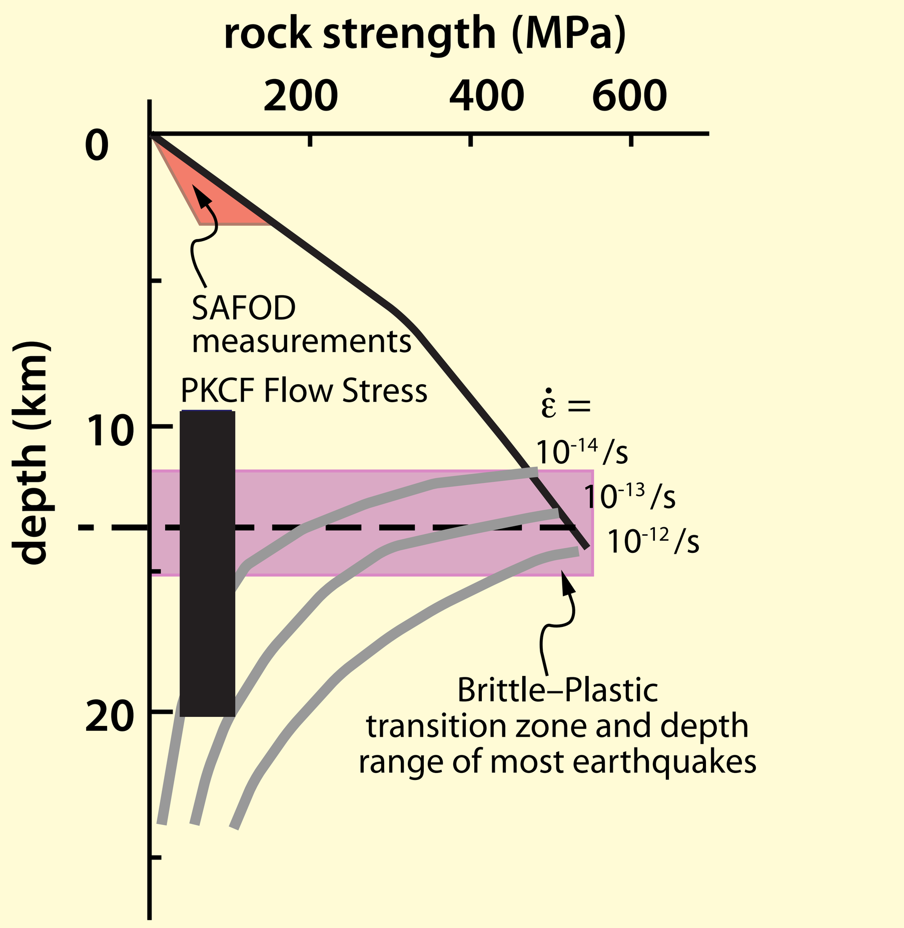
Table 1: List of sample names along with their corresponding grain sizes across horizontal and vertical dimensions (see also histograms to the left). Mean strength (in MPa) is calculated from the Stipp and Tullis (2003) quartz piezomter.

Sample	Age (Ma)	TitaniQ Temp (˚C)	Depth (km)	Strain Rate Min. (s-1)	Strain Rate Max. (s-1)	Rock Type
03B1	86	?	12	2.83E-18	7.76E-17	Granite
03B2	86	465 +/-22	12	3.71E-17	1.02E-15	Granite
03G	300–200	?	?			Phyllite
02A2	88	480 +/-18	11			Granodiorite
02B	94	479 +/-28	11	7.22E-18	3.85E-16	Alaskite
02H	95	486 +/-7	~11	5.92E-17	1.55E-16	Granite
02H2	?	434 +/-36	~11			Quartz Vein
02I	300–200	414 +/-4	?			Quartzite
02F	104	475 +/-14	12			Granite
10D	92	510 +/-20	20			Granodiorite
10F	92	533 +/-29	20			Granodiorite
11A	102	523 +/-12	17			Tonalite
11F	103	509 +/-31	16			Granite
11H	103	483 +/-41	16	4.56E-17	1.43E-14	Granite

Table 2: List of samples with complete descriptions, including rock types, their ages, and depth of emplacement. Their temperatures of deformation, grain sizes (see Table 1), and depths were used to calculate strain rate along the fault when it was active, ca. 90 Mya.

Sample 10D, a granodiorite, showing extreme deformation.

Sample 03B1, a strongly sheared granite.



The black line is the predicted line of rock strength with depth. The coral colored wedge at the top represents actual rock strength measured in a drill core in the San Andreas Fault. The section highlighted in pink is the brittle-plastic transition zone at which depth most earthquakes are found to occur. The black rectangle is the calulated depth and strength of the rock samples examined in this study.

Conclusions

1. Deformed quartz grain sizes vary with depth along the Kern Canyon fault, from 10 to 35 micrometers. The rocks with smaller grain sizes came from samples taken in the middle of the shear zone. This indicates that rocks in fault zones are very weak at depths from 10 to 20 km.
2. The results from TitaniQ show that the temperature of recrystallization of the samples increases with the depth of rock exposed.
3. By using both the stress exerted on the rocks as well as their deformation temperatures, the sample strain rates were found to lie between a minimum of 7.2×10^{-18} per second to a maximum of 1.4×10^{-14} per second. These values overlap the observed strain rates of the modern-day Denali fault in Alaska and the San Andreas fault in California, which are around 3.2×10^{-18} and 1.6×10^{-14} strain per second, respectively.
4. Further work that I hope to complete on this project is to measure grain sizes for the samples from deeper levels of the fault zone further south. I would also like to run more samples in the the electron microprobe to determine deformation temperatures for more samples.

Acknowledgements

Thank you to URSA for funding me in my research as well as giving me an opportunity to present my work. Also thank you to Mary Keskinen for general petrology knowledge. A special thanks to Adrienne Kentner for working with me on the electron microprobe for hours and teaching me general petrology knowledge as well. This project would never have been possible without much guidance from Elisabeth Nadin. Thanks!

References

Hirth, Greg, Christian Teyssier, W. James Dunlap. "An Evaluation of Quartzite Flow Laws Based on Comparisons Between Experimentally and Naturally Deformed Rocks." International Journal of Earth Sciences. 90 (2001): 77-87. Springer-Verlag.

Nadin, Elisabeth, Jason Saleeby. "Disruption of regional primary structure of the Sierra Nevada batholith by the Kern Canyon fault system, California." The Geological Society of America. 438 (2008): 1-26. The Geological Society of America.

Stipp, Michael and Jan Tullis. "The Recrystallized Grain Size Piezometer for Quartz." Geophysical Research Letters. 30. 21 (2003). American Geophysical Union.